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A STELLAR COMPANION IN THE HD 189733 SYSTEM WITH A KNOWN TRANSITING EXTRASOLAR PLANET

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ABSTRACT

We show that the very close-by (19 pc) K0 star HD 189733, already found to be orbited by a transiting giant planet, is the primary of a double-star system, with the secondary being a mid-M dwarf with projected separation of about 216 AU from the primary. This conclusion is based on astrometry, proper motion and radial velocity measurements, spectral type determination and photometry. We also detect differential proper motion of the secondary. The data appear consistent with the secondary orbiting the primary in a clockwise orbit, lying nearly in the plane of the sky (that is, nearly perpendicular to the orbital plane of the transiting planet), and with period about 3200 years.

Subject headings: stars: low-mass, brown dwarfs – stars: individual: HD 189733 – stars: individual: HD 189733B – planetary systems – binaries (including multiple)

1. INTRODUCTION

Of the $\sim$ 170 exoplanets in 146 planetary systems known at the present time[4], the majority ($\sim$ 160) are revealed only by the reflex velocity of their parent stars, (e.g. Mayor & Queloz 1995; Marcy & Butler 1996), yielding their periods, eccentricities, semi-major axes, and $m \sin i$ values. However, a small number (9) of the known exoplanets transit their host stars, so that the inclination ambiguity is removed and – assuming a mass and radius for the primary – their actual mass and radius, hence their mean density may be determined.

A number of the known exoplanets have been found to occur in multiple stellar systems. The small sample of 22 such systems form an important class of objects (for references, see: Eggenberger et al. 2004b, 2005; Mugrauer et al. 2004a,b, 2005a). Until now, however, no planet found in a multiple stellar system also transits its parent star. In this Letter, we note that the parent star of the recently-discovered transiting extra-solar planet HD 189733b (Bouchy et al. 2005, hereafter B05) is itself a member of a double-star system.

In §2 we present the evidence that the star HD 189733 has a physical companion star. Specifically, §2.1 shows that it has a common proper-motion companion; §2.2 shows that the companion's radial velocity is the same as HD 189733 within uncertainties; and §2.3 shows that the companion is a red dwarf star which must lie at approximately the same distance as HD 189733. For these combined reasons the co-moving companion, now labeled HD 189733B, almost certainly must be a true physical companion. In §3 we detect a differential proper motion, and obtain an initial estimate of the orbital motion of HD 189733B about HD 189733. Finally, §4 discusses some implications of this finding, and avenues for future work.

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[4] http://vo.obspm.fr/exoplanetes/encyclo/index.php

2. EVIDENCE THAT HD 189733 HAS A PHYSICAL COMPANION STAR

HD 189733 is a close-by ($D = 19.3 \pm 0.3$pc) K0 dwarf, with mass of $0.82 \pm 0.03 M_{\odot}$ and other properties as described in B05. The 2MASS survey (Cutri et al. 2003) lists a nearby red star, 2MASS 20004297+2242342 ($\mathrm{J} = 10.12 \pm 0.04$, $\mathrm{H} = 9.55 \pm 0.08$, $\mathrm{K_S} = 9.32 \pm 0.03$, $\mathrm{J} - \mathrm{K_S} = 0.8$), some 3.7 magnitudes fainter in $\mathrm{K_S}$ and 5 magnitudes fainter in V (estimated from J, H, $\mathrm{K_S}$). This star has an angular separation of 11.2″ from HD 189733, lying 10.2″ W and 4.6″ to the S.

HD 189733 is not listed in the Washington Double Star Catalogue (WDS; Mason et al. 2001), but here we will show that 2MASS 20004297+2242342 is in fact its physical companion; in anticipation of that result we henceforth denote the companion as HD 189733B. Note that the latter name is distinct from HD 189733b, the name given by B05 to the planetary companion to HD 189733. Our conclusion that the two stars form a bound binary system is based on the following evidence.

2.1. *Common Proper Motion*

HD 189733 has a relatively high proper motion of $\mu_{\alpha} = -2.49 \pm 0.68\ \mathrm{mas\,yr^{-1}}$ and $\mu_{\delta} = -250.81 \pm 0.53\ \mathrm{mas\,yr^{-1}}$(Hipparcos; Perryman et al. 1997). To determine whether HD 189733 and HD 189733B share common proper motion, and hence may be members of the same physical system, we have inspected the following archival material: i) the digitized Palomar Observatory Sky Survey (POSS) scans[5] (POSS-I, 1951 R-band; POSS-II, 1990 R-band, 1992 B-band, and 1996 I-band); ii) the HST QuickV survey (1982, R-band), iii) the 2MASS[6] 2000 J-, H- and K-band scans (Skrutskie et al. 2000). In addition, in November 2005, we used the TopHAT telescope of the HAT Network at the Fred Lawrence Whipple Observatory (FLWO), to obtain I-band images. We also acquired 8 short exposure I-band frames in December 2005 with KeplerCam on the 1.2m telescope at FLWO.

[5] http://archive.stsci.edu/cgi-bin/dss_form
[6] http://irsa.ipac.caltech.edu/

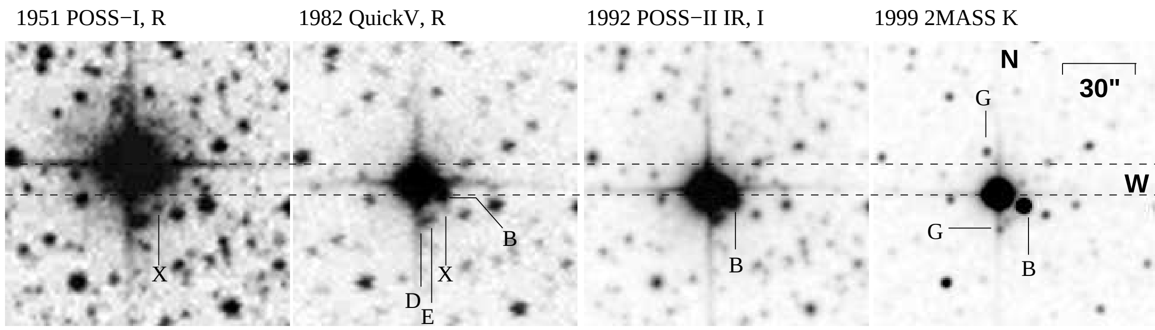

Fig. 1.— HD 189733 in four different epochs on registered frames. The known proper motion to the South is well visible. The upper dashed line shows the declination in 1951, and the lower dashed line for 1999. The companion HD 189733B is not visible on the POSS-I frame (left panel) because HD 189733 is over-saturated and the scan resolution is not adequate. HD 189733B (indicated by **B**) is visible on the rest of the panels, displaced to the SW by $\sim 11''$ from HD 189733; it is seen increasingly better from left to right, as the companion is relatively brighter at increasingly longer wavelengths (R, I and K bands). "X" denotes a faint star visible on POSS-I and the QuickV scans, before the Southward moving HD 189733B merges with it. "D" and "E" mark two faint stars that are visible on all of the frames, but one of the artificial filter glints ("G") merges with their position on the 2MASS frame.

We used our home-grown FIHAT software environment (Pál et al. 2006, in preparation) to find sources on all the above images (∼50 isolated, non-saturated stars), cross-match them by rejecting outliers, determine the astrometric mapping between the images, and transform them to the same reference system. Visual inspection of the registered frames show i) the prominent Southward proper motion of HD 189733 (in harmony with the Hipparcos values), ii) a much fainter co-moving companion that we identify as HD 189733B (for details, see Fig. 1). The companion is clearly separated from HD 189733 on the 2MASS J, H and K scans (Fig. 1, right panel), and is listed in the 2MASS point source catalogue as 2MASS 20004297+2242342. Although not illustrated on Fig. 1, the co-movement is also demonstrated by the TopHAT and FLWO 1.2m I-band frames. No other co-moving companion is detected on these frames.

To quantify the proper motion of HD 189733B, we have carried out astrometry on the QuickV, POSS-II, 2MASS, TopHAT and FLWO1.2m observations. We used the 2MASS catalogue as astrometric reference, where the quoted position uncertainty of bright, isolated sources is 120mas. We used the previously established pixel centers of $\sim$ 50 un-saturated stars that we found by fitting Gaussian profiles. By running our FIHAT/FISTAR star-finder algorithm on artificially generated frames, we found typical errors of the centroid positions to be on the order of 0.05pix (corresponding to $0.08''$ on QuickV, $0.05''$ on POSS-II and 2MASS, and $0.1''$ on TopHAT and $0.07''$ on FLWO1.2m). We then derived the second order astrometric mappings between the X,Y coordinates and the 2MASS astrometric reference (HD 189733(B) were omitted from the fit), and used this to transform the pixel coordinates of the frames to the ICRS (α, δ; Seidelmann & Kovalevsky 2002) system used by 2MASS. The rms around the fit was $\sim 0.2''$ for QuickV, $\sim 0.18''$ for POSS-II, $\sim 0.05''$ for 2MASS, $\sim 0.3''$ for TopHAT, and $0.1''$ for the FLWO1.2m, respectively.

The derived proper motion of HD 189733B is $\mu_{\alpha,B} = -4.1{\pm}9\,\mathrm{mas\,yr^{-1}}$, $\mu_{\delta,B} = -264{\pm}12\,\mathrm{mas\,yr^{-1}}$(see Fig. 2), which are within 2σ of the Hipparcos proper motion of HD 189733 itself. Therefore, it is clear that, within uncertainties, HD 189733 and HD 189733B share a common proper motion and so are likely to comprise a bound system.

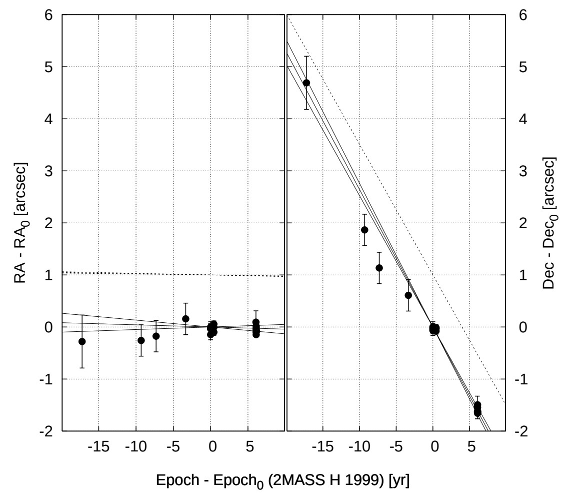

Fig. 2.— Proper motion of HD 189733B in RA (left) and Dec (right) relative to the 2MASS 1999 position. The two panels are on the same scale. The central solid lines show the linear fit to the data; the two other solid lines show the same fits using slope and intersection parameters differing by $\pm 1\sigma$. For reference, the dashed line shows the relative proper motion of HD 189733 from Hipparcos, offset by 1.0 arcsec for clarity.

2.2. *Radial Velocity*

A common radial velocity is a further indication that the two stars are physically associated. In order to test this possibility, we obtained spectroscopic observations of both the primary star and the suspected companion, using the Center for Astrophysics (CfA) Digital Speedometer (DS; Latham 1992) at the 1.5m Tillinghast telescope of FLWO, Arizona.

Seven DS observations have been made of the star HD 189733 dating back to 1995, with the two most recent being 2005 Dec 10 and Dec 17. For each of these a radial velocity was obtained on the CfA Native System velocity reference (Stefanik et al. 1999). The mean and standard deviation of these measurements is $V_{\rm rad} = -2.38 \pm 0.20$ $\mathrm{km\,s^{-1}}$, with no significant evidence for a long-term velocity variation over the past 10 years. For HD 189733B, two DS observations were made, on 2005 Dec 10 and 17, yielding a mean radial velocity $V_{\rm rad,B} = -3.1 \pm 1.0$ $\mathrm{km\,s^{-1}}$. Thus, within observational uncertainties the difference in measured velocities is consistent with the two stars being physical companions.

2.3. *Characteristics of the Star HD 189733B*

There is still a remote chance that the apparent companion could be a distant giant star with high tangential velocity or a very close-by low luminosity and velocity sub-dwarf, that happens to have the same sky position, radial velocity, and proper motion.

While the DS has the primary goal of radial-velocity measurements, correlation of the spectrum with template spectra based on the Kurucz (1993) models also yields information on $T_{\rm eff}$, $\log g$ and stellar rotation $v \sin i$. We obtained $\log g = 4.5 \pm 0.3$ – a value appropriate to a main sequence M dwarf. Correlation with observed spectra of M dwarfs with spectral type ranging from M0.0 to M5.5 gives best correlation near M3.5. We also observed HD 189733B with the FAST spectrograph on the FLWO 1.5m telescope. Visual comparison of the resulting spectra to known M dwarf spectra suggests a spectral type of M4V. Based on its spectral type, plus apparent magnitude, we then infer a distance to HD 189733B consistent with the 19.3 pc distance to HD 189733 .

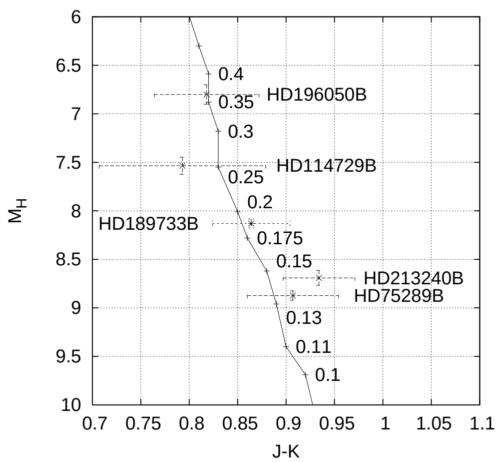

FIG. 3.— Location of HD 189733B on the (Baraffe et al. 1998) 5Gyr isochrone with other M-dwarf binary companions of stars with known planets, plotted from Eggenberger et al. (2004b). Stellar masses are labeled along the isochrone in units of $M_\odot$.

We independently estimated the spectral type of HD 189733B from 2MASS photometry. Because of the slightly overlapping profile of the close-by, bright HD 189733 we performed aperture photometry of HD 189733B on the 1999 2MASS scans after subtracting off the Gaussian profile of HD 189733, and using $\sim$ 50 isolated stars with original 2MASS photometry as reference. This analysis yields $\rm J = 10.147 \pm 0.02$, $\rm H = 9.551 \pm 0.03$, and $\rm K_S = 9.318 \pm 0.02$. These values are within 0.03mag of the 2MASS Point Source Catalogue values, but we find smaller errors, and slightly redder $\rm J - K$ color index. We transformed our measured $\rm J - K_S$ value (namely 0.829 ± 0.03), to $\rm J - K$ on the Bessell and Brett (BB) system following Carpenter (2005), to obtain $\rm (J-K)_{BB} = 0.864 \pm 0.04$. Then we derived the absolute magnitude M_H (8.13 ± 0.045) from our measured H magnitude and an assumed distance equal to that of HD 189733 and plotted these values on the color-magnitude diagram of Mugrauer et al. (2005a), which also plots a 5-Gyr isochrone from Baraffe et al. (1998). The position on the color magnitude diagram (Fig. 3) corresponds to a stellar mass of 0.175 to $0.2 M_\odot$, which according to Cox (2000) corresponds to an M dwarf with spectral type of about M5. The good fit to the isochrone supports our assumption that the distance to HD 189733B is similar to that to HD 189733.

From the above analyses we conclude that HD 189733B is an M dwarf with spectral type in the range M3.5 to M5, with common proper motion, radial velocity, and distance to HD 189733. The relative positions (from astrometry, and assuming equidistance), and relative velocities of the two stars (from proper motion and radial velocity data), along with the $1 M_\odot$ total system mass, are consistent within 2σ with the system being gravitationally bound. Although it would formally be possible for an interloper M dwarf star to be passing very close to HD 189733 at the current epoch, with a relative speed so small as to make it almost gravitationally bound, this possibility is so remote that we conclude that the two stars do indeed form a bound system with projected separation about 216 AU.

3. ORBITAL CHARACTERISTICS OF THE SECONDARY

If the true separation of HD 189733 and HD 189733B is close to the projected separation, and the orbit is circular, and the total system mass is $\sim 1 M_\odot$ ($0.82 M_\odot$ for HD 189733 from B05 and $0.2 M_\odot$ for HD 189733B from §2.3) then the orbital period is $\sim$3200 years, corresponding to $\sim 2 \rm km\,s^{-1}$ orbital motion. For a face on orbit this would yield an observable 22 $\rm mas\,yr^{-1}$ differential proper motion in addition to the co-movement.

In an attempt to detect this, we used two pairs of 2MASS images in the H and K bands obtained in 1999 and 2000 (one of these is the right-hand image in Fig. 1), with mean epoch 2000.073, and compared them with the 8 high resolution I-band frames of the field taken with the FLWO 1.2m telescope at epoch 2005.970. We note that although the other data were useful in confirmation of the common proper motion (as shown in §2.1), because of the saturated HD 189733 image (POSS, Quick-V) and low S/N (TopHAT) they were not used in this precise astrometry aimed at refining the differential proper motion. The astrometry of HD 189733 over the 5.897 year baseline yields a proper motion of $\mu_\alpha = -8 \pm 5$ $\rm mas\,yr^{-1}$ and $\mu_\delta = -245 \pm 8$ $\rm mas\,yr^{-1}$. Because this agrees with the more precise Hipparcos value within uncertainties (§2.1), we adopt that value for the proper motion of HD 189733. For HD 189733B we find $\mu_{\alpha,B} = -3 \pm 5$ $\rm mas\,yr^{-1}$ and $\mu_{\delta,B} = -272 \pm 5$ $\rm mas\,yr^{-1}$, which imply a differential proper motion relative to HD 189733 of $\Delta\mu_\alpha = -1 \pm 5$ $\rm mas\,yr^{-1}$ and $\Delta\mu_\delta = -21.2 \pm 5$ $\rm mas\,yr^{-1}$(Fig. 4).

Formally, the data indicate a detection of relative proper motion at the 4σ level. The position of the companion, and its direction and magnitude of relative motion, are consistent with orbital motion in a clockwise orbit roughly in the plane of the sky.

However, there could be underlying systematic effects due to the different instruments and bandpasses used for the earlier-epoch 2MASS data and the later-epoch FLWO1.2 data. We estimated one of these, namely the effect of stellar profile merging of HD 189733B with HD 189733 that is different on the 2MASS and FLWO1.2m frames. By subtracting off the Gaussian profile of the primary, we found that the derived proper motion of HD 189733B changed by only 2$\rm mas\,yr^{-1}$. Nev-

ertheless, while the detection of orbital motion roughly in the plane of the sky seems secure, it is premature to derive specific orbital parameters for the system.

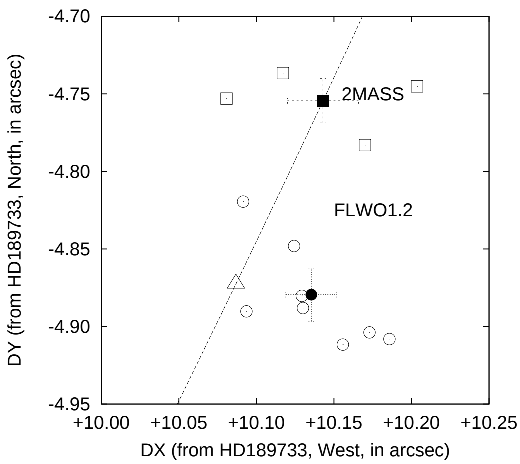

Fig. 4.— Differential proper motion of HD 189733B relative to HD 189733. Open squares and circles indicate individual 2MASS (epoch 2000.073) and FLWO1.2 (epoch 2005.970) data points respectively. Filled square and circle represent the mean of those respective data points, with error bars representing 1 standard deviation of those means. Dashed line depicts a circular orbital path about HD 189733 in the plane of the sky, passing through the 2MASS position. The triangle depicts the position at epoch 2005.973 for such an orbit.

4. DISCUSSION

Several studies have been done on the characteristics of close-in planets orbiting the primary star of a multiple star system. Thus Eggenberger et al. (2004b, and references therein) found a tendency for massive planets ($m \sin i$ greater than $2M_{\rm J}$) to occur preferentially in multiple-star systems. However, HD 189733b is a low-mass planet ($1.15M_{\rm J}$without $\sin i$ ambiguity), and yet it is in a multiple stellar system, thus weakening the distinction between single and multiple stars.

HD 189733b exceeds all other known extrasolar planets in binary systems in its proximity to its parent star (a_{pl}=0.031 AU). However, a number of planets in multiple-star systems are nearly as close (e.g. Tau Boo b, a_{pl}=0.05 AU; HD 75289b, a_{pl}=0.046 AU).

The data suggest (see §3) that the binary orbit is likely to be nearly face on, i.e. the orbital plane would be nearly orthogonal to the orbital plane of the planet HD 189733b, which by virtue of its transit we know to have an inclination of nearly 90°. A detailed calculation based on the relative velocities and positions of the two stars shows that the orbit of HD 189733B and HD 189733b cannot be coplanar at the 4-σ level (Pál et al, in preparation). When additional transiting planets are discovered in multiple star systems, it should be possible to study the relation of the system architecture (e.g. mass, semi-major axis of the stellar secondary) to planet properties in better detail.

Because the HD 189733 system is so close-by, it should be possible to do excellent astrometry over the next few years with modern high precision astrometric techniques from ground or space. The changing radial velocity signal of either or both of HD 189733 and HD 189733B might also be detectable after a few years of monitoring with current high-precision radial velocity devices. High precision proper motion and radial velocity measurements should lead to a good characterization of the orbital characteristics of the binary system and their relation to the orbit of the transiting planet.

Finally, we note that because this system is only 19 pc from Earth and hence both stellar components are unusually bright for their spectral types, many additional follow-on observations requiring high resolution spectroscopy or high precision photometry will be feasible. This should permit a full characterization of the system including the possible detection of additional low mass components.

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